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# Analysis and prediction of copper surface roughness obtained by selective laser melting

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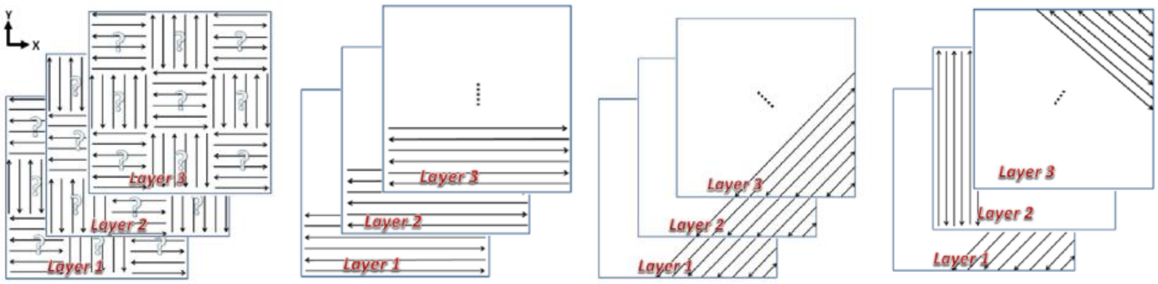
**Abstract.** The paper presents the results of experimental studies of the effect of mechanoactivation of the powder, argon shielding gas and the effect of technological modes of melting: the speed of the laser beam, the power of laser radiation, the scanning step, the preliminary temperature of heating the powder material on the surface roughness of the copper powder material obtained by selective laser melting. Experiments on the melting of copper powder are implemented on the installation of layer-by-layer laser melting of the original design, which allows to adjust all technological modes of melting. The surface roughness is determined on the non-contact digital microscope Olympus LEXT OLS4100. The mathematical dependence of the surface layer roughness of copper powder on the technological modes of melting is obtained on the basis of the theory of experiment planning and static processing of the results. The significant parameters of the regime-the power of laser radiation, the speed of the laser beam, the scanning step affecting the roughness of the layer. The positive effect of mechanical activation of powder material and protective atmosphere on the quality of the surface layer is shown.

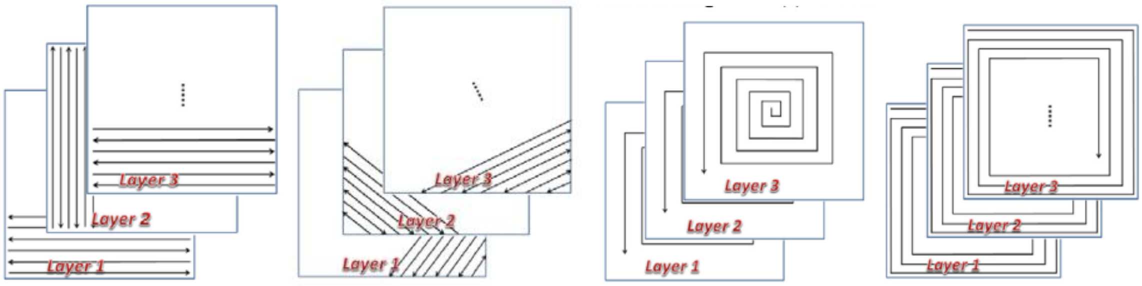
## Introduction

The first commercially successful additive production method was developed in 1987 by Carl Descartes and used to make models and prototypes [1]. Currently, additive technologies are the fastest growing advanced technologies in the world. Unlike traditional methods of material removal, rapid prototyping technologies are aimed at creating complex products by sequentially adding material (materials). By now, a large number of rapid prototyping methods are known which differ in the material used and in the way the product is formed. Innovative is the method of selective laser melting of a physical copy of various objects from metals and alloys based on the 3D CAD-model. The volumetric product is created by layer-by-layer melting of the powdered material laser beam in accordance with the contour of each section. In recent years, the microstructure and mechanical properties of the parts have improved significantly due to improvements in laser processing conditions (increase in laser power, reduction in the diameter of the laser beam, reduction in the thickness of the resulting layer, etc.). Despite significant progress, the technology of selective laser melting still faces surface quality problems [2, 3]. Obtaining a good quality surface is the main issue for preventing delaminating, residual stresses, premature failure.

A review of the literature has shown that the laser power and scanning speed are often presented as the main parameters affecting the surface quality of the product obtained by selective laser sintering [4]. Brecher et al [5] suggested that the scanning speed is preferred in the appointment of modes of melting. The relatively low speed allows for uniform melting of the powder material, but as a result there is a problem of low productivity [6]. Van and co-authors [7] analyzed the effect of scanning speed and pitch to achieve good surface quality. Great importance is given to the impact of scanning strategy. In [8], studies were conducted to assess residual stresses and strains under various scanning strategies for the Nickel-chromium alloy Inconel 718. It is written that the maximum stresses along the x and Y axes were observed in samples with the contour scanning strategy when they were shifted to the center (Fig. 1, h).



(a) Island scanning (b) Line scanning (c) $45^0$ line scanning (d) $45^0$ rotate scanning



(e) $90^0$ rotate scanning (f) $67^0$ rotate scanning (g) In-out scanning (h) Out-In scanning

**Figure 1**. The scan strategy [8].

Significant stresses were formed with a horizontal scanning strategy (Figure 1, h). All samples have a voltage along the X and Y axes between the single layer and the substrate. It was noted that with oblique scanning at an angle of $45^0$, the samples showed slight residual stresses and deformations, in comparison with other scanning strategies (Figure 1, c) [8].

In [9], studies were made of the effect of laser power, the scanning speed, the layer thickness, and the scanning strategy on the surface roughness of the nickel-chromium-iron-molybdenum alloy HASTELLOY X obtained by selective laser melting. It is noted that cohesion has a great influence on the roughness of the surface layer. Coagulation is the fusion of fine powder particles into larger ones under the influence of laser radiation. There was a decrease in coagulation with a decrease in the scanning rate, which is due to an increase in the melting time of the powder and a decrease in the viscosity of the melt. Increasing the scanning step leads to an increase in the surface roughness. The surface roughness has the smallest value of 15 μm at a laser power of 200 W and scanning speed of 3000 mm/s. The authors proposed to improve the roughness of the inclined surface by contour scanning of each layer with increased energy density.

Analysis of the literature showed that the regimes and melting conditions for different materials are determined experimentally and depend on a significant number of parameters [10, 11, 12]. The aim of this paper is to establish the limits in which the surface roughness of a copper powder obtained by selective laser melting can be varied by changing the technological modes of laser processing.

## Materials and methods

Experiments on the melting of copper powder are implemented on the installation of layer-by-layer laser melting of the original design, which allows to adjust all technological modes of melting. The device is a technological laser complex for the formation of surfaces of products of complex spatial shape, consisting of ytterbium fiber laser LK – 100 – V, three-coordinate table, personal computer, CNC system and original software. Ytterbium fiber laser with a wavelength of 1.07 microns allows you to adjust the power from 10 to 100 watts. The quality and accuracy of the manufactured products provide constant output power and focus accuracy of the fiber laser. Control of the laser beam with a special program in the working area of 100x100x100 mm allows scanning on any given contour. On the body of the installation, for applying a layer of powder in the melting zone, the carriage and leveling rollers are fixed. Inside the carriage there is a powder hopper that allows you to adjust the density of the applied layer. The powder layer is scanned by the laser beam along the required trajectory at the specified modes. After receiving a single layer, the table is lowered by a stepper motor to the layer thickness [13]. With the help of a carriage, the platform is filled with powder material to form the next layer. The cycle is repeated until the complete creation of the product, then the table is moved to its original position and the finished part is removed. To eliminate the interaction of the powder with oxygen and nitrogen, it is possible to supply a protective gas to the laser melting zone.

Copper stabilized powder is widely used in various fields of industry. The powder particles have a spherical shape with a nominal size of 0.007 mm, bulk density of 1.25-1.9 g/cm3. The roughness of the layer was determined by a microscope OLYMPUS LEXT OLS 4100.

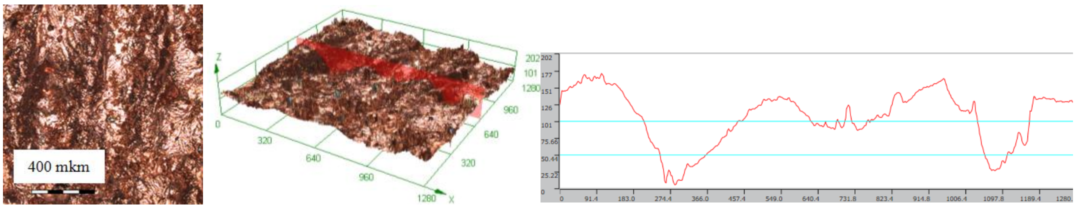
During the experiment, the technological modes of melting were changed: the power of laser radiation, scanning speed, scanning step, the temperature of heating the powder composition. Studies have been conducted on the influence of argon protective gas and mechanical activation of powder on the roughness of the surface layer of the copper powder obtained by the method of selective laser melting. The protective environment allows to exclude interaction of powder products with oxygen and nitrogen, and also to strengthen a surface of a product. Mechanical activation is used to increase the dispersion, the presence of defects in the crystal lattice of the powder [14]. Mechanical processing of the powder was carried out in the centrifugal-planetary mill AGO-2.

## Results and discussions

At the first stage, preliminary exploratory experiments were carried out to determine the acceptable melting modes. Under them meant modes when a single layer did not crumble, i.e. had some mechanical strength without significant deformation. Experiments have shown that the laser power is less than 14 W and the laser beam speed is more than 3000 mm/min are insufficient for melting the powder material. Power more than 30 W and speed less than 200 mm/min leads to intensive oxidation and ignition of the powder. Scanning step of more than 0.3 mm does not allow single tracks to be sintered together, which prevents the formation of a single layer. Increasing the temperature of heating the powder material has a positive effect on the strength of the single layer.

To establish the empirical dependence of the layer roughness of copper powder on the technological modes of melting, a four-factor experiment was carried out on the program of the second order central composite planning. For this purpose, sixteen experiments of the four-factor experiment were implemented; seven experiments were conducted in the center of the plan and supplemented with eight experiments in "star" points. Copper powder was determined by the following ranges of conditions of melting are: the radiation power P=(14-30) W, the moving speed of the laser beam V=(200-3000) mm/min, scanning step s=(0.1-0.3) mm; the heating temperature of the powder composition varied in the range t=(26-200) $^{0}$C. Surface roughness was determined using a digital contactless microscope Olympus LEXT OLS4100, figure 2.

Figures 3-8 show the effect of technological regimes and conditions of melting on the appearance of the surface of a single layer of copper powder obtained by selective laser melting.



*а* *б* *в*

**Figure 2.** Determination of surface roughness on the microscope Olympus LEXT OLS4100:

a-photo of a single layer of copper powder obtained by selective melting in the following modes: P=30 W, V=2000 mm / min, s=0.2 mm, t=300$^{0}$C; b-cross section of the surface profile; b-profilogram of the surface layer Rz, µm.

The effect of laser power on the surface roughness of a single layer is shown in figure 3. The power increase from 14 to 30 W at V=1600 mm/min, s=0.2 mm leads to a change in Rz from 480 to 725 µm.

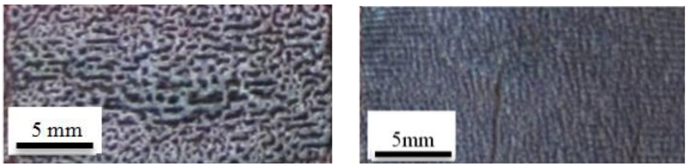


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**Figure 3.** Photos of the surface of a single layer of copper powder obtained by selective melting at the modes:
a-P=30 W, V=1600 mm/min, t=114 $^{0}$C, s=0.2 mm, Rz=725 µm,
b-P=14 W, V=1600 mm/min, t=114 $^{0}$C, s=0.2 mm, Rz=480 µm.

The effect of the laser beam velocity on the surface roughness of a single layer is shown in figure 4. Increasing the speed from 200 to 3000 mm/min at P=22 W, s=0.2 mm leads to a change in Rz from 750 to 480 microns. In figure 4, a there are areas of uniform powder melting.

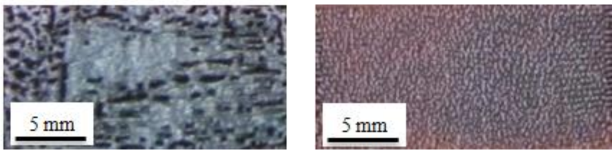

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**Figure 4.** Photos of the surface of a single layer of copper powder obtained by selective melting at the modes:
a- P=22 W, V=200 mm/min, t=114 $^{0}$C, s=0.2 mm, Rz=750 µm,
b- P=22 W, V=3000 mm/min, t=114 $^{0}$C, s=0.2 mm, Rz=480 µm.

The effect of the heating temperature of the powder material on the surface roughness of a single layer is shown in figure 5. The temperature increase from 20 to 200 $^{0}$C at P=30 W, V=3000 mm / min, s=0.3 mm leads to a change in Rz from 540 to 525 microns.

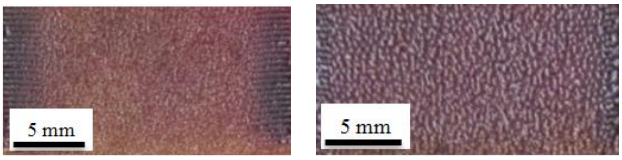

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**Figure 5.** Photos of the surface of a single layer of copper powder obtained by selective laser melting at the modes:
a- P=30 W, V=3000 mm/min, t=200 $^{0}$C, s=0.3 mm, Rz=525 µm,
b- P=30 W, V=3000 mm/min, t=20 $^{0}$C, s=0.3 mm, Rz=540 µm.

The effect of the scanning step on the surface roughness of a single layer is shown in figure 6. Increasing the scan step from 0.1 to 0.3 mm at P=30 W, V=3000 mm / min, t=200 $^{0}$C leads to a change in Rz from 740 to 525 microns.

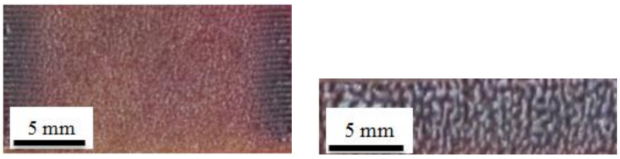

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**Figure 6.** Photos of the surface of a single layer of copper powder obtained by selective laser melting at the modes:

a- P=30 W, V=3000 mm / min, t=200 $^0$C, s=0.3 mm, Rz=525 µm,
b- P=30 W, V=3000 mm / min, t=200 $^0$C, s=0,1 mm, Rz=740 µm.

Figure 7 shows the effect of shielding gas on the surface roughness of a single layer. During the sintering of copper powder in argon, a change in the color of the sintered surface was observed, it acquired a Golden color and the surface roughness of Rz decreased from 650 to 500 µm.

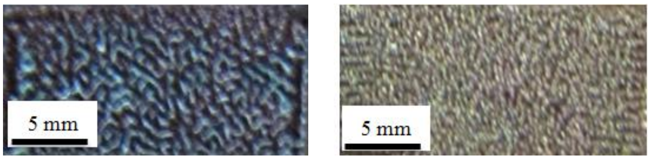

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**Figure 7.** Photos of the surface of a single layer of copper powder obtained by selective melting in different modes:

a- P=22 V, V=1600 mm / min, t=114 $^0$C, s=0.3 mm, Rz=650 µm, air sintering;
b- P=22 V, V=1600 mm / min, t=114 $^0$C, s=0.3 mm, Rz=500 µm, sintering in argon.

Influence of mechanical activation of powders on the surface roughness of a single layer is shown in figure 8. The effect of laser radiation on the powder subjected to three-minute activation leads to a decrease in the diameter of the coagulated particles and their uniform distribution over the surface. Surface roughness is significantly reduced from 600 to 125 microns, at P=14 W, V=200 m/ min, t=20 $^0$C, s= 0.1 mm.

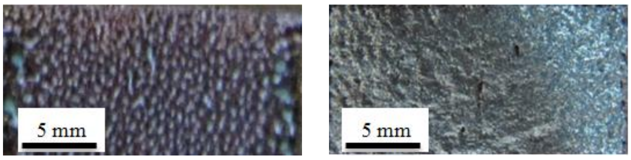

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**Figure 8.** Photos of the surface of a single layer of copper powder obtained by selective melting: a-P=14 W, V=200 mm/min, t=20 $^0$C, s=0,1 mm, Rz=600 µm; b – P=14 W, V=200 mm / min, t=20 $^0$C, s=0,1 mm, Rz=125 µm, after three minute activation.

As a result of planning and conducting experiments and static processing [15] the results obtained, the mathematical dependence of the surface roughness of the copper powder on the melting regimes is obtained, which allows identifying significant parameters:

$$R_Z = 356 + 15 \cdot P - 0.1 \cdot V - 0.057 \cdot t + 425 \cdot S \qquad (1)$$

The dependence of the roughness of a single layer on the melting modes is shown in figure 9 [16, 17].

The roughness of the surface layer of copper powder is significantly affected by the speed of the laser beam. The change in V from 200 to 3000 mm / min leads to a decrease in Rz by 56.25%, at P=22 W, s=0.2 mm, t=114 $^0$C, in accordance with figure 4. Power also has a big impact on Rz. Increasing P from 14 to 30 W $R_Z$ increases by 62%, at V=1600 mm / min, t=114 $^0$C, S=0.2 mm, figure 3. Change S from 0.1 to 0.3 mm reduces Rz by 40%, at P=30 W, t=200$^0$C, V=3000 mm / min, according to figure 6. The heating temperature of the powder material on the Rz affects slightly.

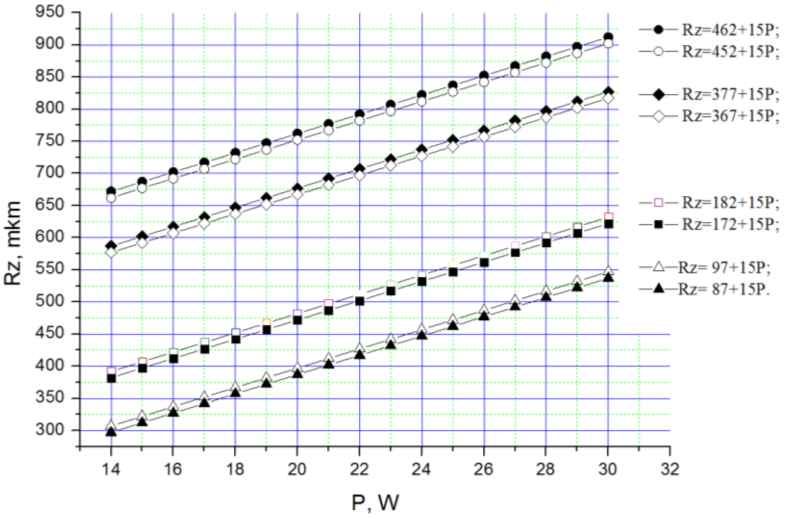

**Figure 9.** Diagram of the influence of melting modes on the roughness of a single layer *Rz* :
-●- V=200 mm/min, t=26 $^0$C, S=0.3 mm; -○- V=200 mm/min, t=200 $^0$C, S=0.3 mm;
-◆-V=200 mm/min, t=26 $^0$C, S=0.1 mm; -◇- V=200 mm/min, t=200 $^0$C, S=0.1 mm;
-□- V=3000 mm/min, t=26 $^0$C, S=0.3 mm; -■- V=3000 mm/min, t=200 $^0$C, S=0.3 mm;
-△-V=3000 mm/min, t=26 $^0$C, S=0.1 mm; -▲- V=3000 mm/min, t=200 $^0$C, S=0.1 mm.

Thus, the speed of the laser beam, the laser radiation power and the scanning step are the main parameters that affect the roughness of the sintered surface layer of copper powder.

## Conclusion

The conducted research allowed to determine the rational areas of technological modes of selective laser melting of copper powder: P=(14-30) W, V=(200-3000) mm/min, s=(0.1-0.3) mm; t=(26-200) $^0$C, to determine the nature of the effect of selective laser melting modes and to obtain an empirical dependence of the roughness of a single surface layer of copper powder, which allows to control the melting process in order to obtain a quality product. The positive effect of protective atmosphere and mechanical activation of metal powder materials on the quality of the surface layer is noted. To reduce roughness, improve internal structure and strength properties, melting is recommended to be carried out in argon using metal powder materials subjected to mechanical activation. The studies show that the roughness of the surface layer Rz can be changed within significant limits, changing the technological modes of laser processing. The roughness of the sintered surface layer of PMS-1 is most influenced by the speed of the laser beam. The change in V from 200 to 3000 mm / min leads to a decrease in Rz by 56.25%, at P=22 W, s=0.2 mm, t=114 $^0$C. Power also has a big impact on Rz. Increasing P from 14 to 30 W $R_Z$ increases by 62%, at V=1600 mm/min, t=114 $^0$C, S=0.2 mm. Change S from 0.1 to 0.3 mm reduces Rz by 40%, at P=30 W, t=200$^0$C, V=3000 mm / min. the temperature of heating of the powder material on Rz affects slightly. Thus, the speed of the laser beam, the laser radiation power and the scanning step are the main parameters that affect the roughness of the sintered surface layer of copper powder.

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